Information Theoretic Comparison of MIMO Wireless Communication Receivers in the Presence of Interference

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Abstract Multiple-input multiple-output (MIMO) wireless communication provides a number of advantages over traditional single-input single-output (SISO) approaches, including increased data rates for a given total transmit power and improved robustness to interference. Many of these advantages depend strongly upon the details of the receiver implementation. For practical communication systems a competition between communication performance and computational complexity exists. To reduce computation complexity, suboptimal receivers are commonly employed. In this paper, the details of a variety of receivers are incorporated into the effects of the channel so that information-theoretic performance bounds can be exploited to evaluate receiver approaches. The performance of these receivers is investigated for a range of environments. Two classes of environments are considered: first, channel complexity, characterized by the shape of the narrowband channel-matrix singular-value distribution, and second, external interference. Receiver approaches include minimum-mean-squared error, minimum interference, and multichannel multiuser detection (MCMUD), given various assumed limitations on channel and interference estimation. Receiver performance implications are also demonstrated using experimental data.

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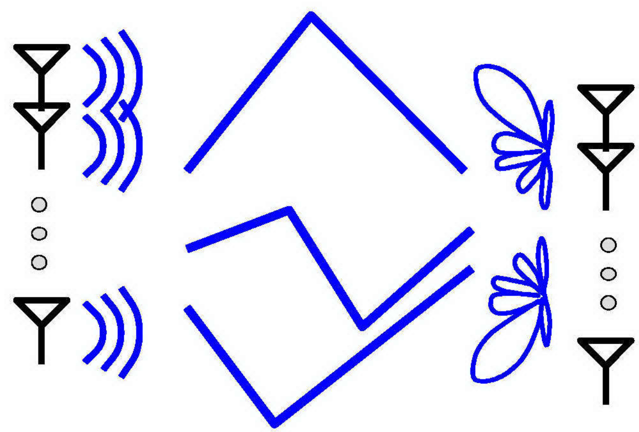
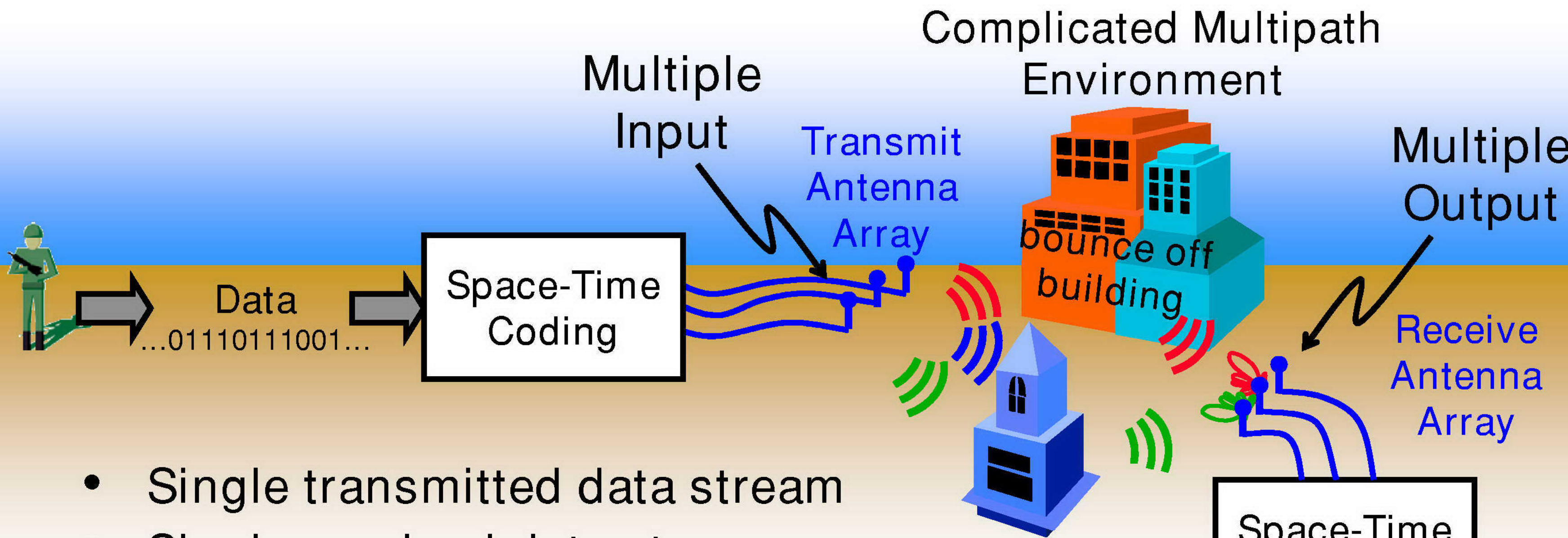
Topics
MIMO Communication

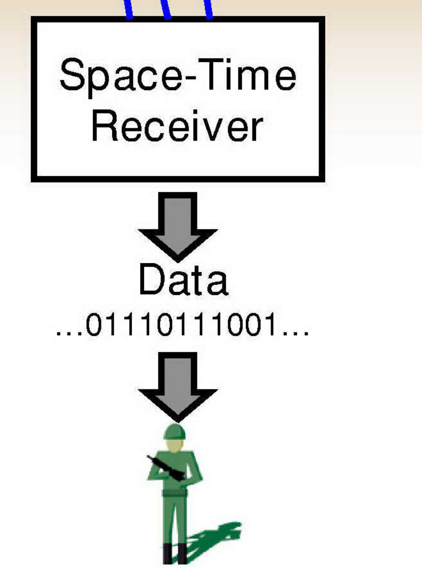
- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison



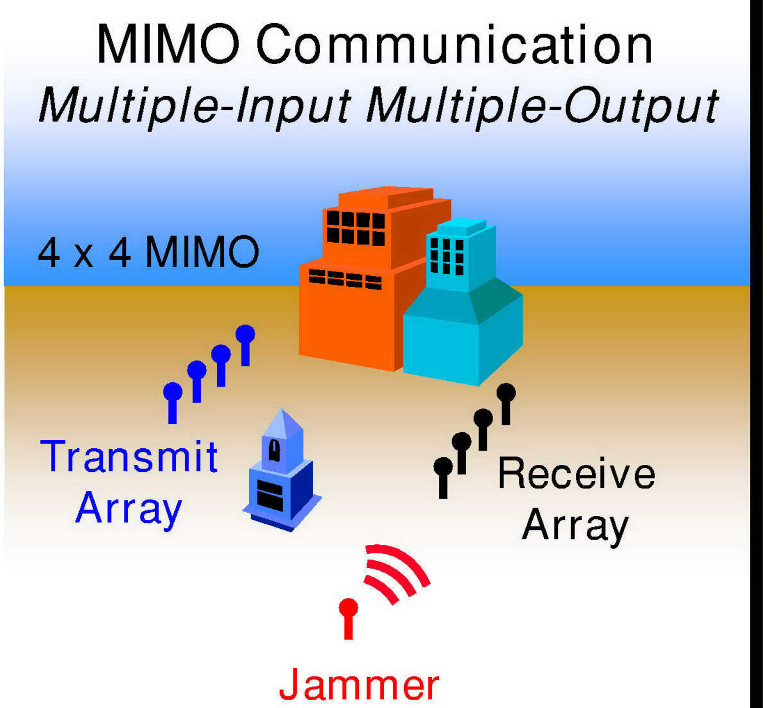
MIMO Communication
Multiple-Input Multiple-Output



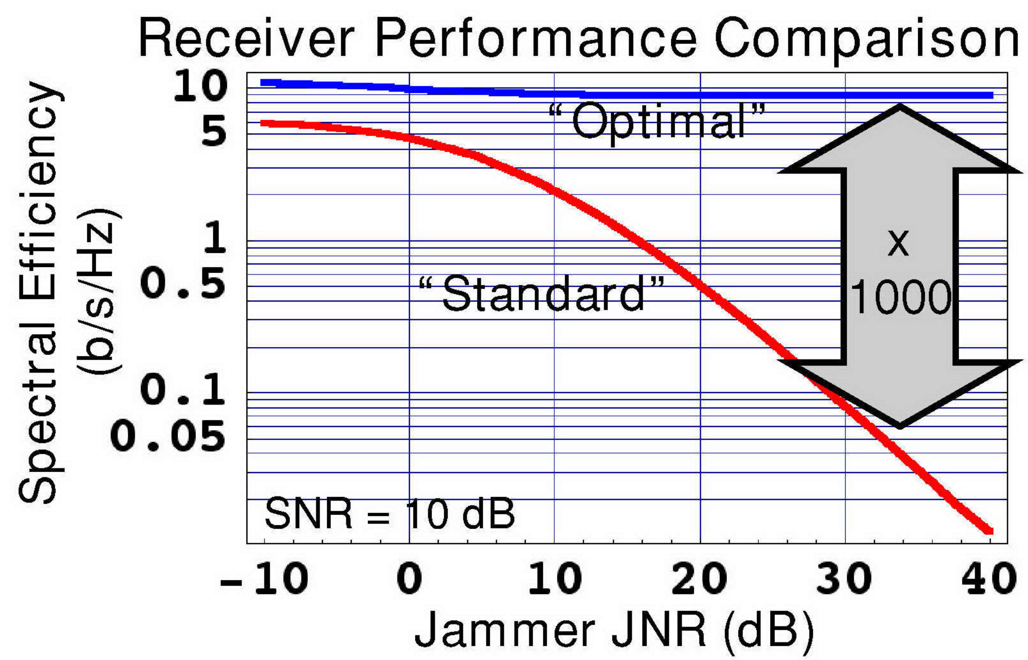
- Single transmitted data stream
- Single received data stream
- Employ multiple modes through environment
- Potential advantages over single-input single-output
  - Diversity
  - Robustness to interference
  - Spectral efficiency



Not All MIMO Receivers Are Equal



- "Standard" MIMO receivers perform badly in difficult environments
  - Ignore the possibility of jamming or external interference
  - Lower computational complexity
- "Optimal" MIMO receiver barely affected by jamming



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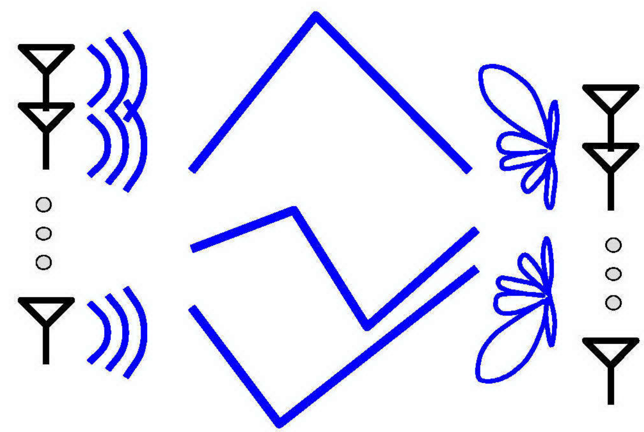
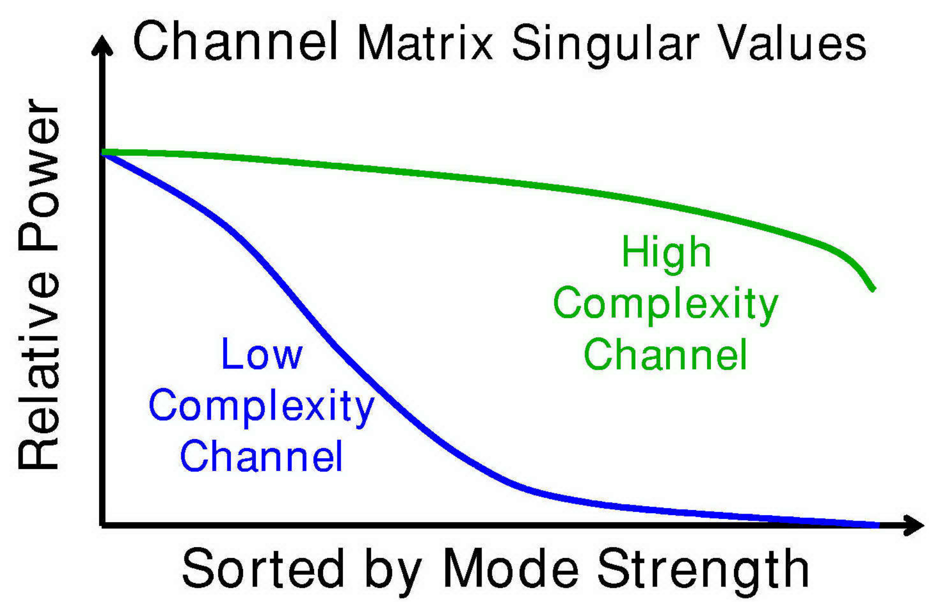


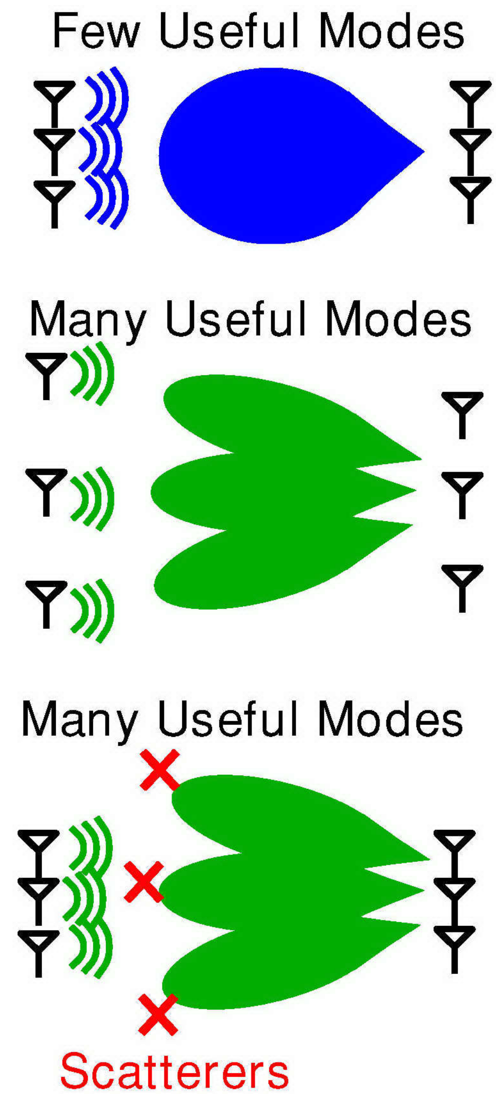
The Channel Matrix

- Channel matrix, H, contains complex attenuation between each transmit and receive antenna

$$\vec{z}(t) = \mathrm{H}\,\vec{x}(t) + \vec{n}(t)$$

- Large channel matrix singular values are useful



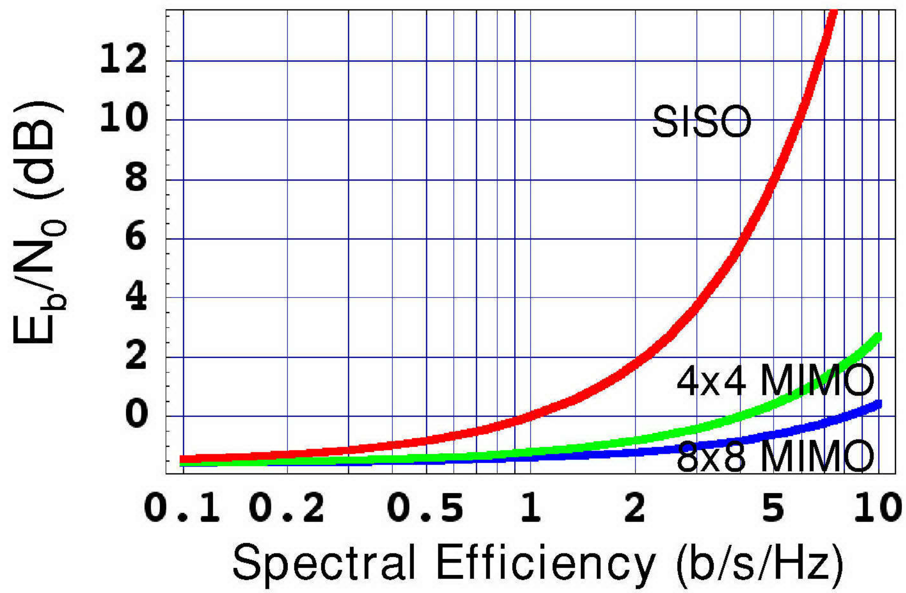


MIMO Capacity Bound(s)

SISO

$$C_{SISO} = \log_2(1 + \mathrm{SNR})$$

Shannon Limit



Informed Transmitter

$$C_{IT} = \max_{\mathrm{P}\,;\, tr\mathrm{P} = P_o} \log_2 \left| \mathrm{I} + \mathrm{H}\mathrm{P}\mathrm{H}^{\dagger} \right|$$

Uninformed Transmitter

$$\mathrm{P} \rightarrow \frac{P_o}{n_T}\mathrm{I}$$

$$C_{UT} = \log_2 \left| \mathrm{I} + \frac{P_o}{n_T}\mathrm{H}\mathrm{H}^{\dagger} \right|$$

$$= \sum_m \log_2 \left(1 + \frac{P_o}{n_T} \| s_m \|^2 \right)$$

Channel Singular Values

Channel Complexity Parameterization

- Gaussian channel matrix, $\mathbf{G}$
- Simulate more realistic eigenvalue distributions by introducing spatial correlation
  - Parameterized by α
- Modified parameterized random channel matrix, $\mathbf{F}$

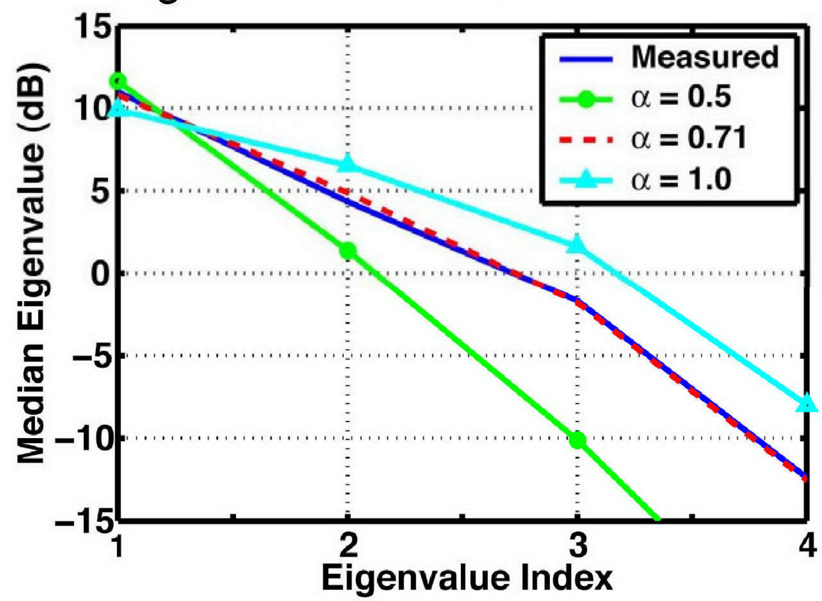
Introduce Spatial Correlation

$$\mathbf{F} = a\,\overbrace{\mathbf{U}\,\mathbf{A}_\alpha\,\mathbf{U}^\dagger}\,\mathbf{G}'\,\overbrace{\mathbf{V}\,\mathbf{A}_\alpha\,\mathbf{V}^\dagger}$$

$$= a\,\mathbf{U}\,\mathbf{A}_\alpha\,\mathbf{G}\,\mathbf{A}_\alpha\mathbf{V}^\dagger$$

$$\mathbf{A}_\alpha = \sqrt{n}\frac{\mathrm{diag}\{\alpha^0, \alpha^1, \cdots, \alpha^{n-1}\}}{\sqrt{\mathrm{tr}\left\{\mathrm{diag}\{\alpha^0, \alpha^1, \cdots, \alpha^{n-1}\}^2\right\}}}$$

Eigenvalue Distribution of $\mathbf{FF}^\dagger$



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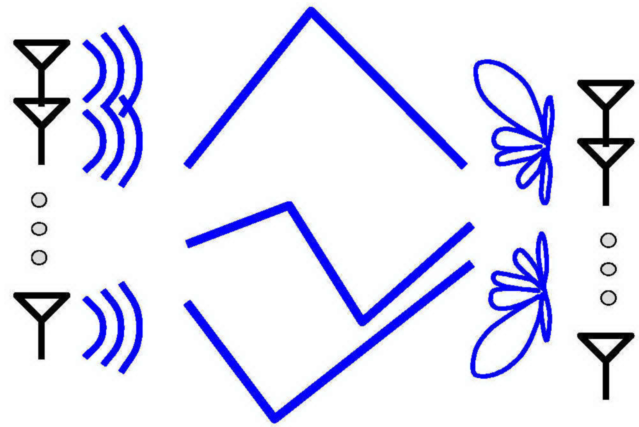
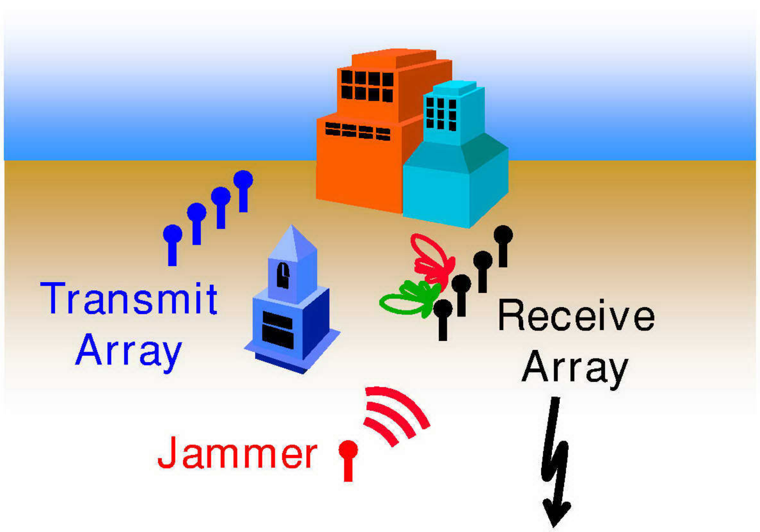
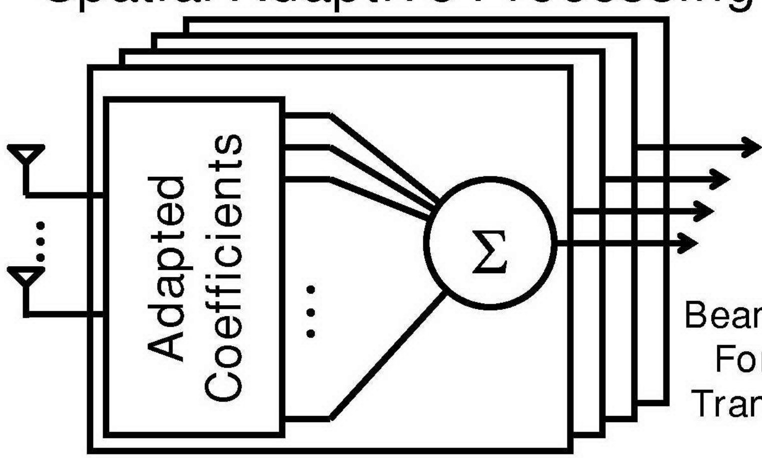


Adaptive Beamforming Receivers

Suboptimal



Spatial Adaptive Processing



Beamformer For Each Transmitter

Beamformer Outputs

$$\vec{z}' = \mathbf{W}^{\dagger}(\mathbf{H}\vec{x} + \vec{n})$$

$$\mathbf{W} \equiv (\vec{w}_1 \ \vec{w}_2 \ \cdots \ \vec{w}_{n_T})$$

Minimum Mean Squared Error

$$\vec{w}_n^{MMSE} \propto \left(\mathbf{I} + \underbrace{\mathbf{R}}_{\text{If Known}} + \frac{P_o}{n_T}\mathbf{H}\mathbf{H}^{\dagger}\right)^{-1} \vec{h}_n$$

Minimum Interference

Standard MIMO Receiver

$$\vec{w}_n^{MI} \propto \mathbf{P}_n^{\perp}\vec{h}_n$$

$$\mathbf{P}_n^{\perp} = \mathbf{I}_{n_R} - \overline{\mathbf{H}}_n(\overline{\mathbf{H}}_n^{\dagger}\overline{\mathbf{H}}_n)^{-1}\overline{\mathbf{H}}_n^{\dagger}$$

$$\mathbf{H} \equiv \left(\vec{h}_1 \ \overline{\mathbf{H}}_1\right)$$

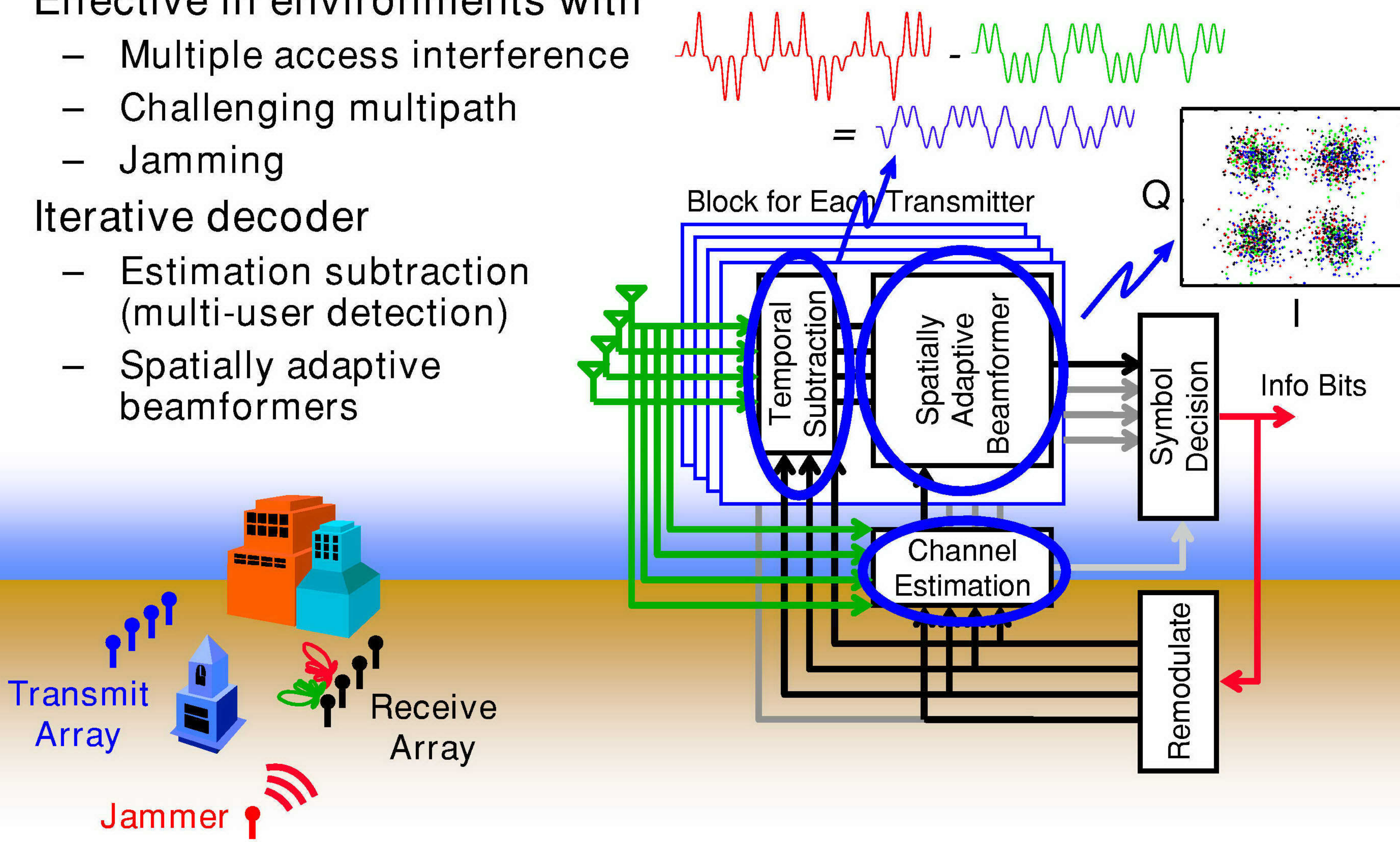
or

$$\vec{w}_n^{MI} \propto \min \operatorname{eigenvec}\left\{\mathbf{R} + \frac{P_o}{n_T}\overline{\mathbf{H}}_n\overline{\mathbf{H}}_n^{\dagger}\right\}$$

Multi-Channel Multi-User Detection (MCMUD)

"Optimal" MIMO Receiver

- Effective in environments with
  - Multiple access interference
  - Challenging multipath
  - Jamming
- Iterative decoder
  - Estimation subtraction (multi-user detection)
  - Spatially adaptive beamformers



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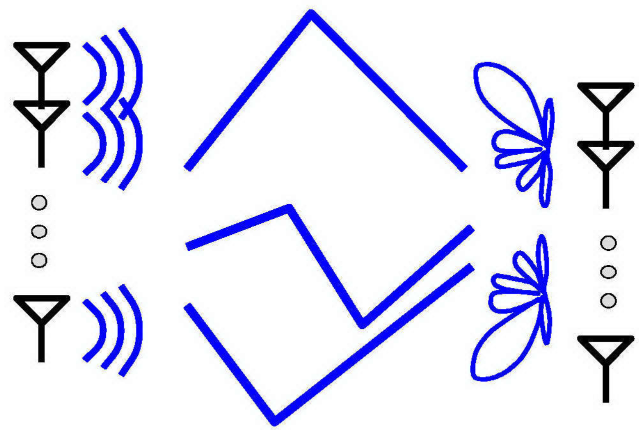

Information Theoretic Capacity
Optimal

Signal Model

$$\vec{z} = \mathbf{H}\vec{x} + \vec{n}$$

Mutual Information

$$\begin{aligned}\mathcal{I}(\vec{z}, \vec{x}|\mathbf{H}) &= h(\vec{z}|\mathbf{H}) - h(\vec{z}|\vec{x}, \mathbf{H}) \\ &= h(\vec{z}|\mathbf{H}) - h(\mathbf{H}\vec{x} + \vec{n}|\vec{x}, \mathbf{H}) \\ &= h(\vec{z}|\mathbf{H}) - h(\vec{n})\,,\end{aligned}$$

Receive-Signal Entropy

$$\begin{aligned}h(\vec{z}|\mathbf{H}) &= \log_2 \left|\pi\, e\, \langle \vec{z}\vec{z}^\dagger \rangle\right| \\ &= \log_2 \left|\pi\, e\, \sigma_n^2 \left(\mathbf{I}_{n_R} + \mathbf{H} \langle \vec{x}\vec{x}^\dagger \rangle \mathbf{H}^\dagger\right)\right|\end{aligned}$$

Noise-Like Entropy

$$\begin{aligned}h(\vec{n}) &= \log_2 \left|\pi\, e\, \langle \vec{n}\vec{n}^\dagger \rangle\right| \\ &= \log_2 \left|\pi\, e\, \sigma_n^2 \mathbf{I}_{n_R}\right|\end{aligned}$$

In Interference Environment

$$h(\vec{z}|\mathbf{H}) \leq \log_2 \left\{\pi e \left|\sigma_n^2 \mathbf{I} + \sigma_n^2 \mathbf{R} + \mathbf{H} \langle \vec{x}\vec{x}^\dagger \rangle \mathbf{H}^\dagger\right|\right\}$$

$$h(\vec{z}|\vec{x}, \mathbf{H}) \leq \log_2 \left\{\pi e \left|\sigma_n^2 \mathbf{I} + \underbrace{\sigma_n^2 \mathbf{R}}_{\text{Interference Covariance Matrix}}\right|\right\}$$

Uninformed Transmitter Capacity

$$C_{UT} \;=\; \log_2 \left|\mathbf{I}_{n_R} + \frac{P_o}{n_T} \tilde{\mathbf{H}}\tilde{\mathbf{H}}^\dagger\right| \quad ; \quad \tilde{\mathbf{H}} \equiv (\mathbf{I} + \mathbf{R})^{-1/2}\, \mathbf{H}$$

Whitened Channel Matrix

Beamformer Receiver Extension to Information Theoretic Bounds

Signal Model

$$\vec{z} = \mathbf{H}\vec{x} + \vec{n} \longrightarrow \vec{z}' = \mathbf{W}^\dagger(\mathbf{H}\vec{x} + \vec{n})$$

$$\mathbf{W} \equiv (\vec{w}_1 \ \vec{w}_2 \ \cdots \ \vec{w}_{n_T})$$

Noise-Like Entropy

$$h_{uc}(\vec{z}'|\vec{x}, \mathbf{H}) \to \sum_l h_{uc}(\vec{z}'|x_l, \mathbf{H})$$

Doesn't take into account correlations between beamformer outputs

$$= \sum_m^{n_T} \log_2 \left(\pi e \sigma_n^2 \vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m \right) \quad ; \quad \mathbf{H} \equiv \left(\vec{h}_1 \ \overline{\mathbf{H}}_1 \right)$$

Receive-Signal Entropy

$$h_{uc}(\vec{z}'|\mathbf{H}) = \sum_m^{n_T} \log_2 \left(\pi e \sigma_n^2 \left[\vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m + \frac{P_o}{n_T} \vec{w}_m^\dagger \vec{h}_m \vec{h}_m^\dagger \vec{w}_m \right] \right)$$

Receiver Beamformer Capacity

$$C_{uc} = \sum_m^{n_T} \log_2 \left[1 + \left(\vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m \right)^{-1} \frac{P_o}{n_T} \|\vec{w}_m^\dagger \vec{h}_m\|^2 \right]$$

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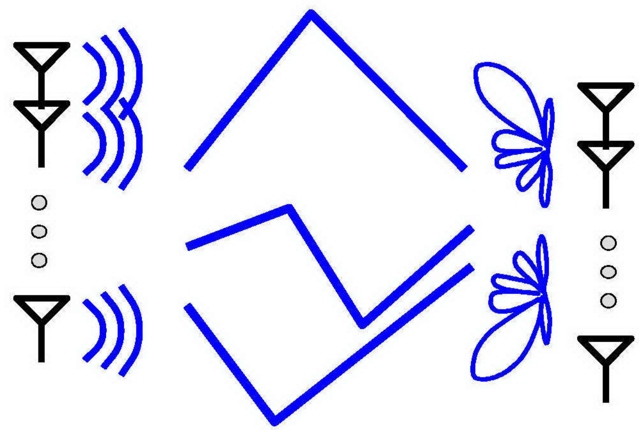
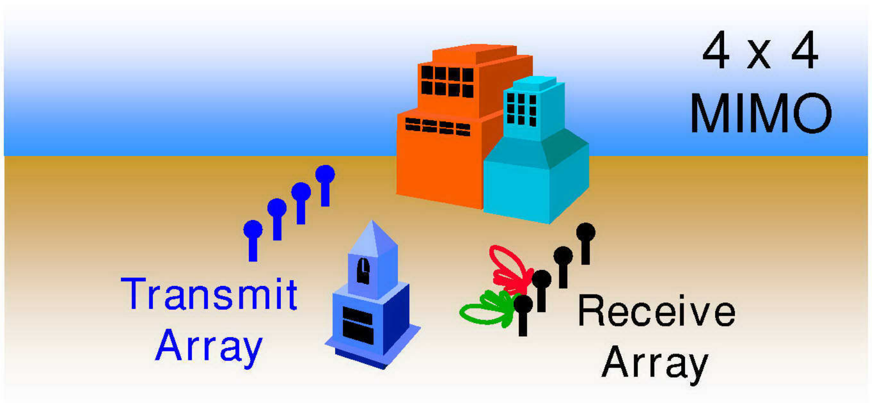
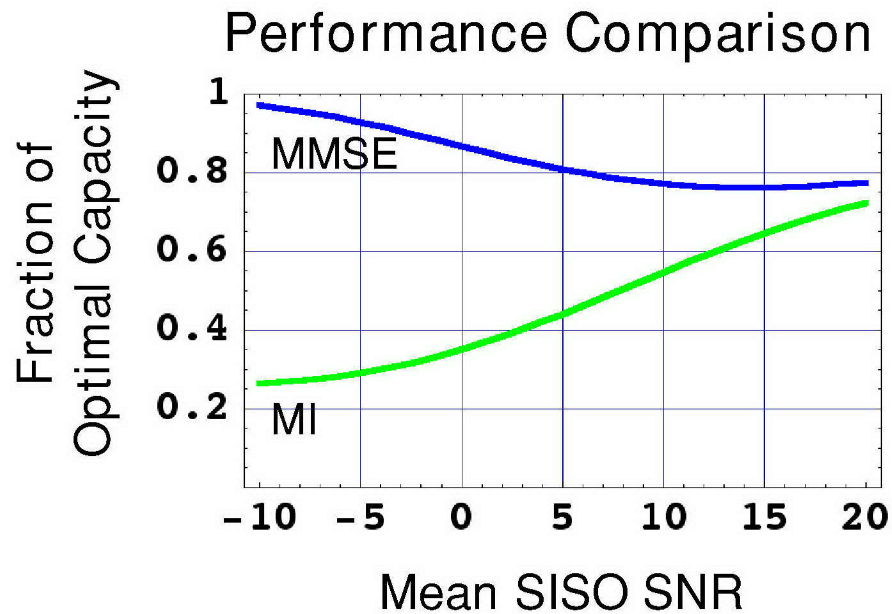
- Performance Comparison
  - Benign
  - Channel Complexity
  - MIMO Interference
  - Jamming
  - Experimental



Performance Comparison
Benign Environment (No Interference)





Minimum Mean Squared Error

$$\vec{w}_n^{MMSE} \propto \left(\mathbf{I} + \mathbf{R} + \frac{P_o}{n_T}\mathbf{H}\mathbf{H}^\dagger\right)^{-1} \vec{h}_n$$

or

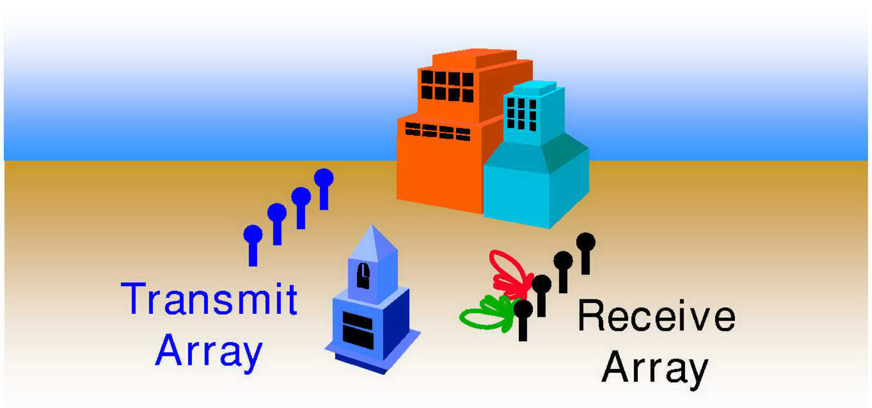
Minimum Interference

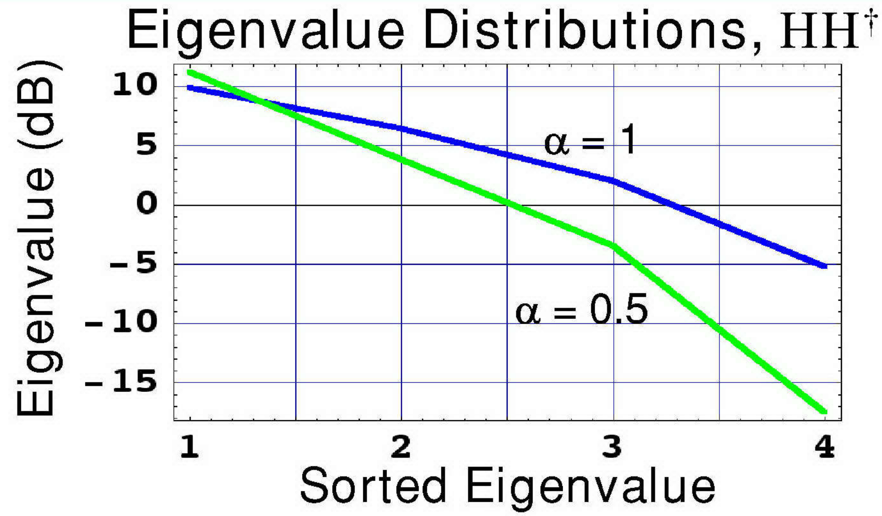
$$\vec{w}_n^{MI} \propto \mathbf{P}_n^{\perp}\vec{h}_n$$

Versus MCMUD

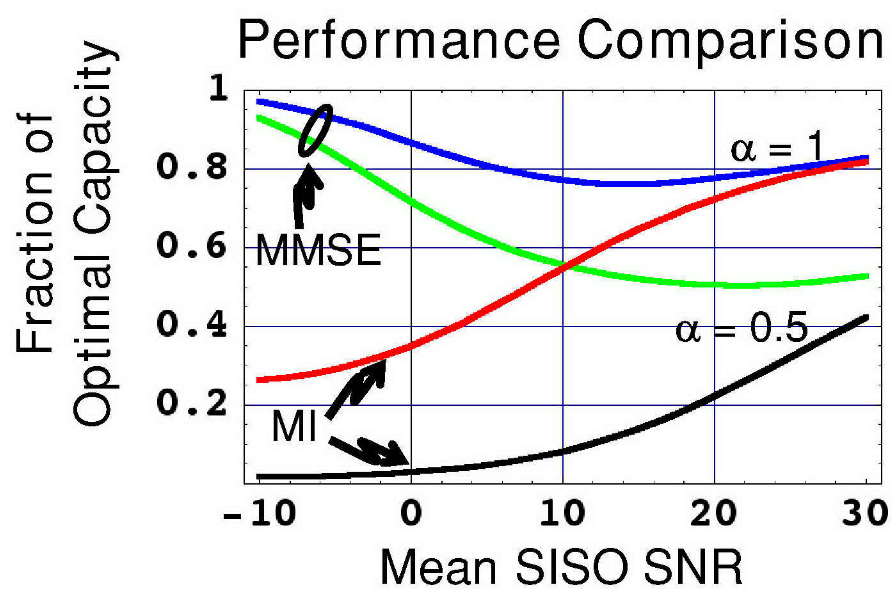
- MMSE has only slight loss compared to MCMUD
- MI performs badly particularly at lower SNR

Performance Comparison
Function of Channel Complexity

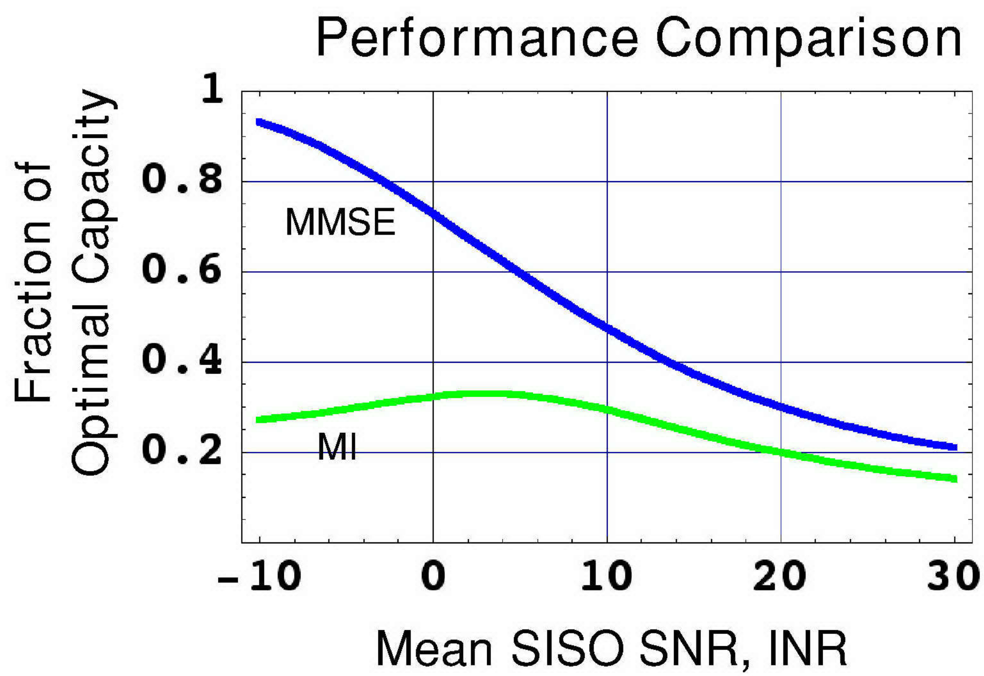




- Study 2 regimes of channel complexity
  - — $\alpha = 1$
  - — $\alpha = 0.5$
- Significant losses for both MI and MMSE at lower channel complexity

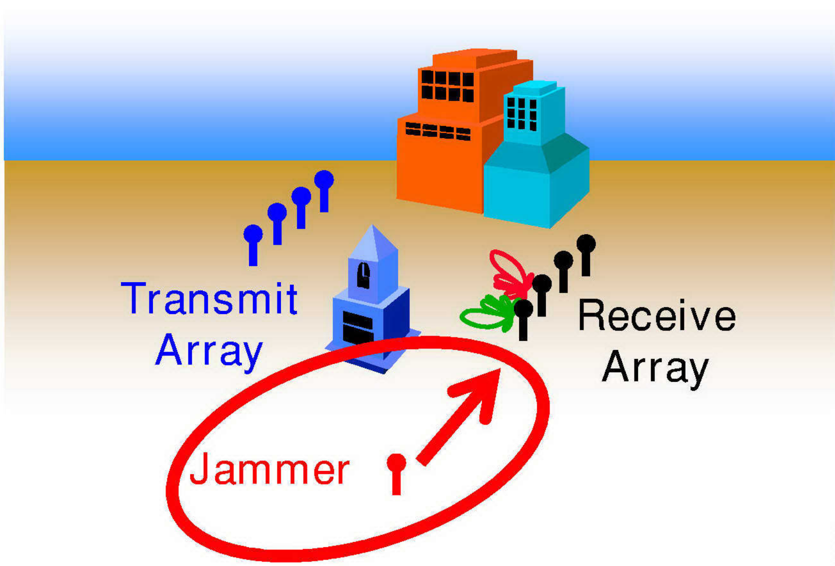


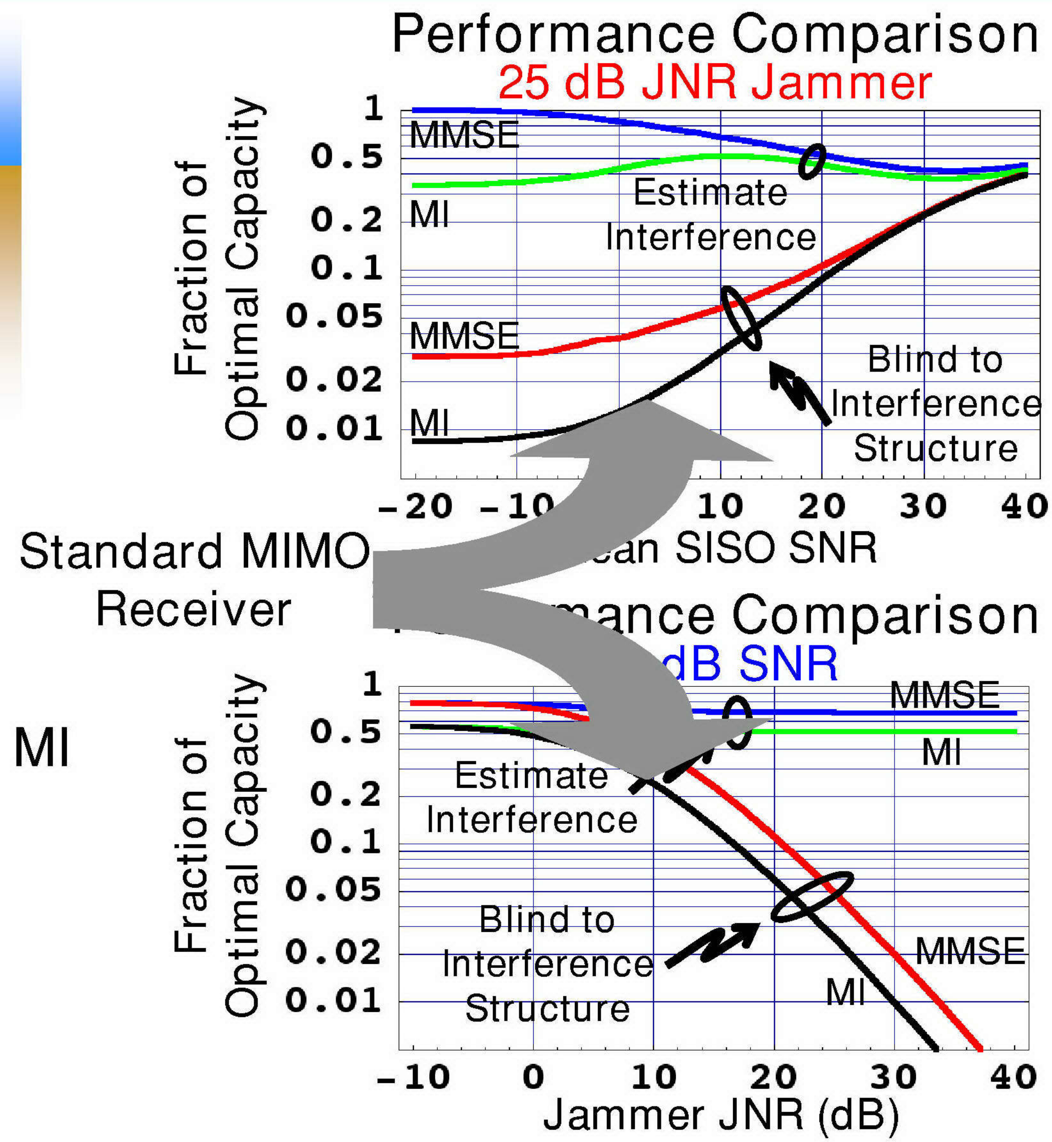
Performance Comparison
Effects of Interference



- Second interfering MIMO transmitter
  - Equal transmit power
- MI performs bad at all SNR
- Both MMSE and MI perform badly compared to MCMUD at high SNR
  - More strong signals than antennas

Performance Comparison
Effects of Jammer



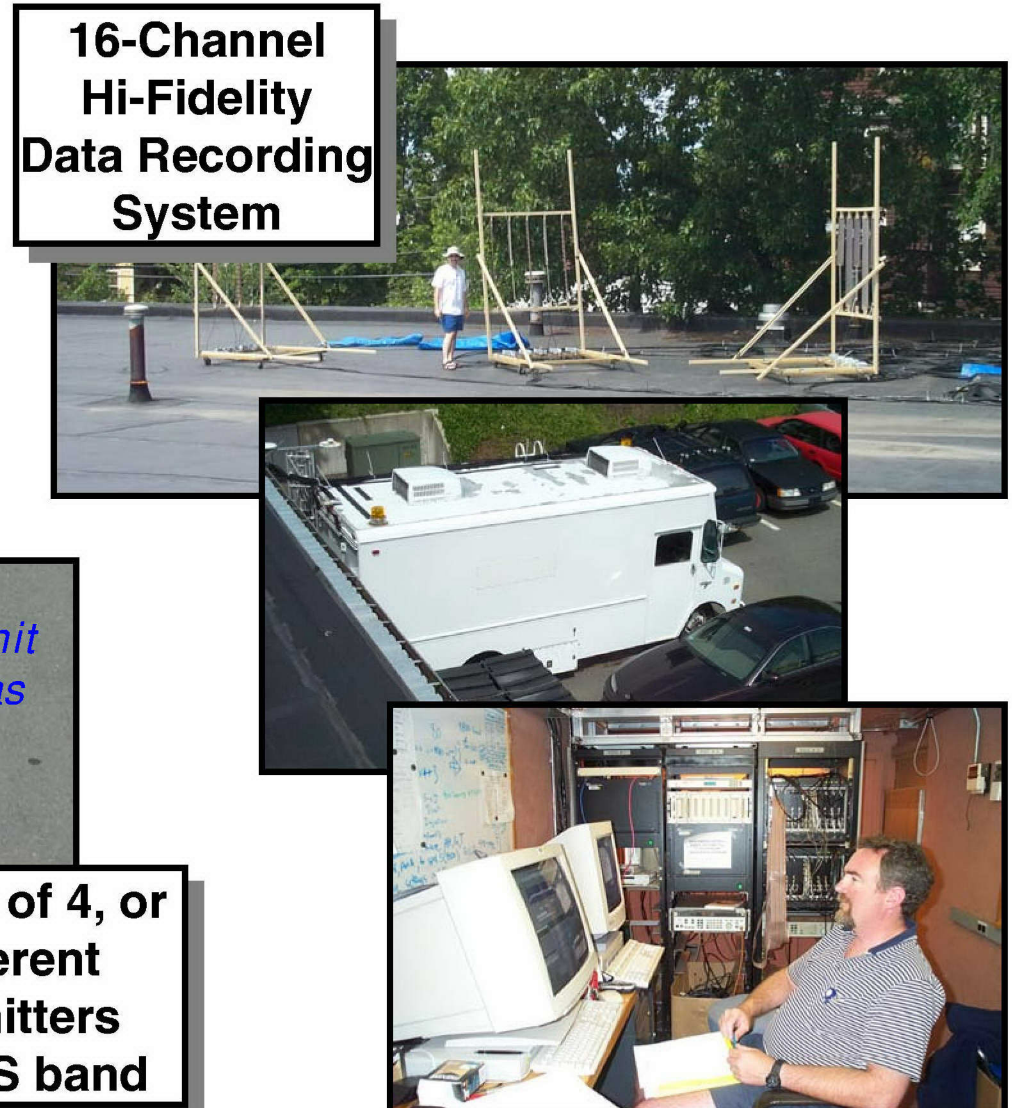


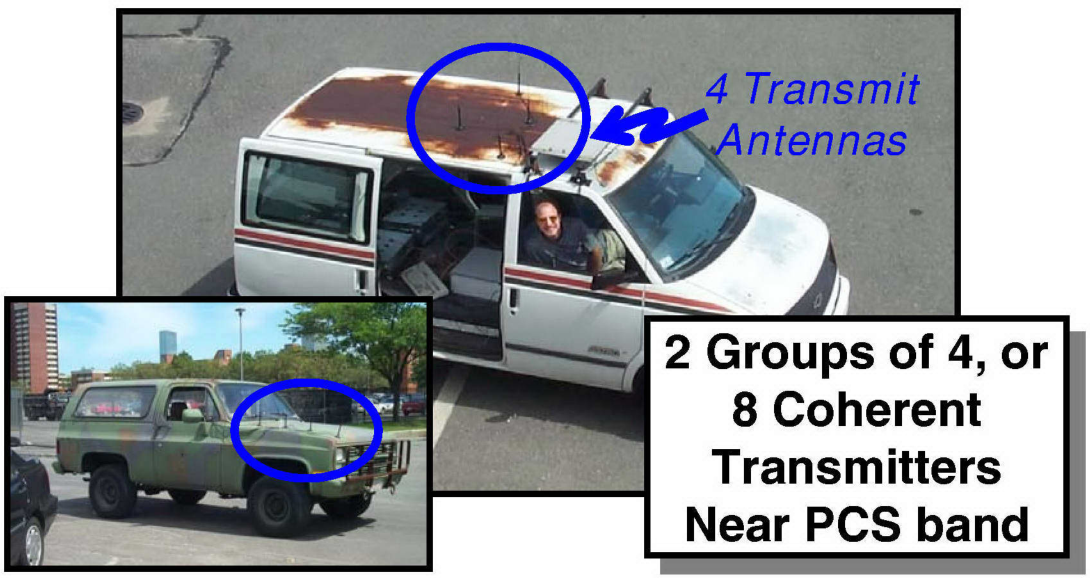
- Significant losses for both MI and MMSE over most SNR
- Terrible performance for receivers that are blind to interference structure

MIMO Experiment

Summer 2002

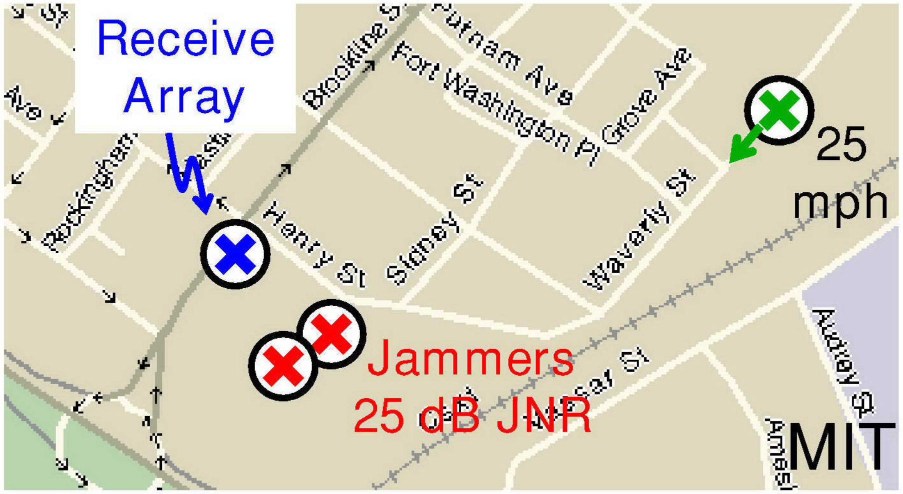
- Investigate channel phenomenology
- Study space-time coding
- Explore transmitter coherence requirements
- Demonstrate robustness to
  - Jamming
  - Cochannel interference



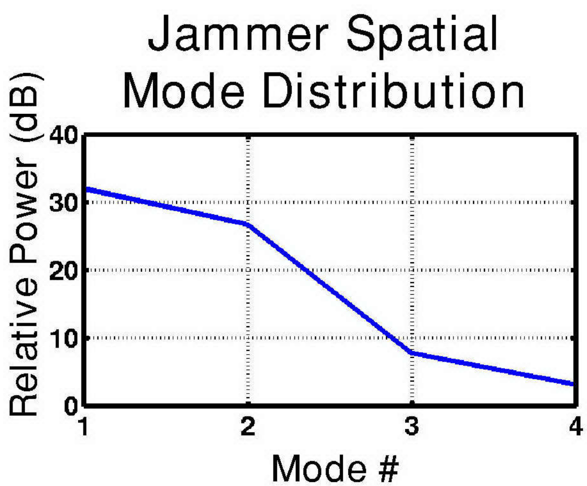


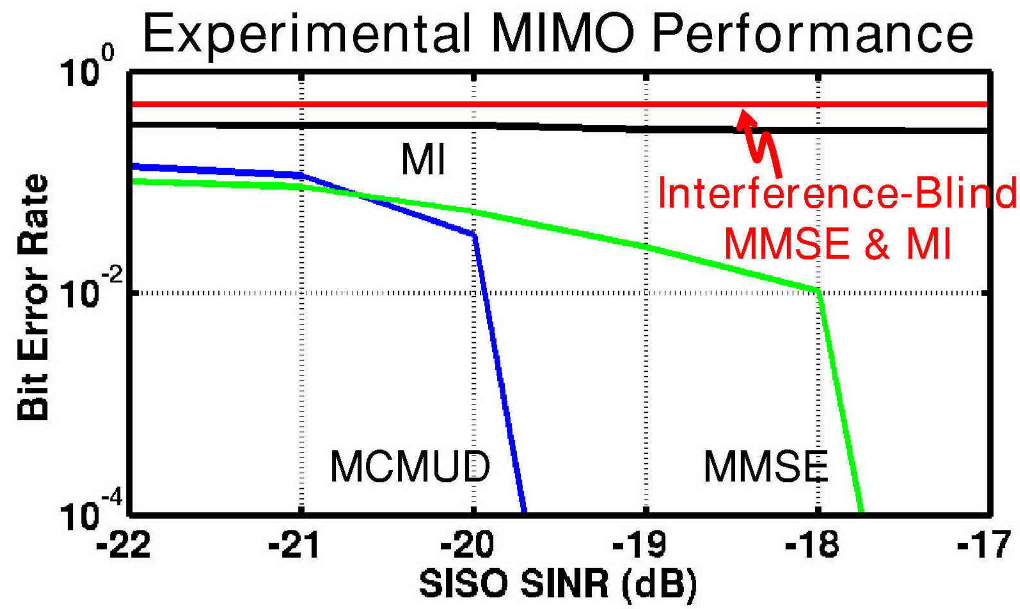
4x4 MIMO Performance

Motion, Jammers, and LO Errors



- 2 Noise Jammers (25 dB JNR)
- Moving transmitter (25 mph)
- Error-free 2b/s/Hz data-link
- MCMUD near performance of jammer-free environment!
- Interference-blind & MI receivers perform badly





Summary

- Presented overview of robust MIMO communication
- Introduced bounds for variety of MIMO receivers
  - MMSE
  - MI
  - MCMUD
- MCMUD advantage significant in many environments
  - Spatially correlated channels (rate improvement > 70)
  - Interference (rate improvement > 5)
  - Jamming (rate improvement > 1000)
- Demonstrated experimental MCMUD immunity to jamming

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- Experiment team
  - Sean Tobin, Jeff Nowak, Lee Duter, John Mann, Bob Downing, Peter Priestner, Bob Devine, Tony Tavilla, Andy McKellips, Gary Hatke
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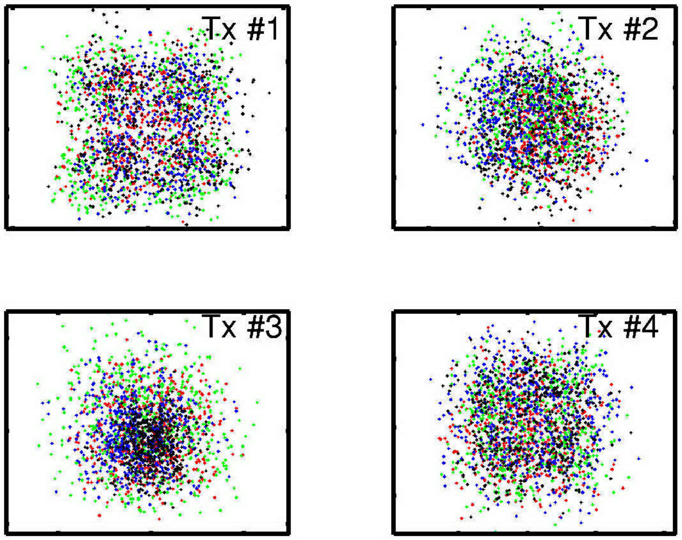
  - Keith Forsythe, Peter Wu, Ali Yegulalp
- Analysis support
  - Amanda Chan
- Students
  - Nick Chang (U. Mich),
    Naveen Sunkavally (MIT)

Backups

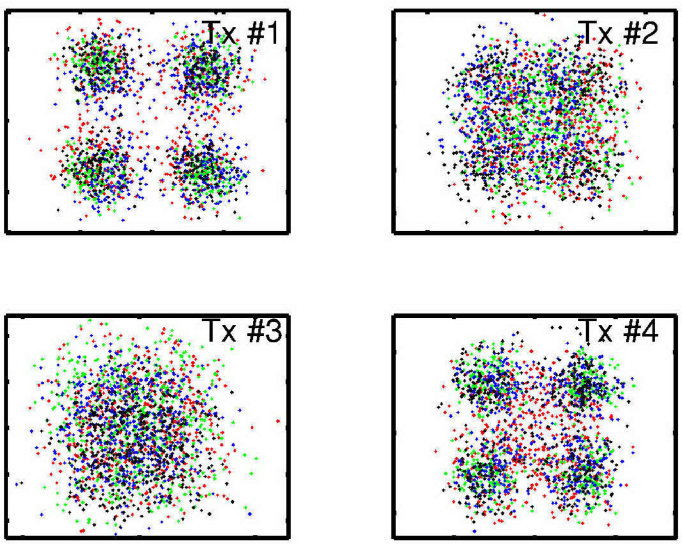
Experimental Results

Successive MCMUD Iterations

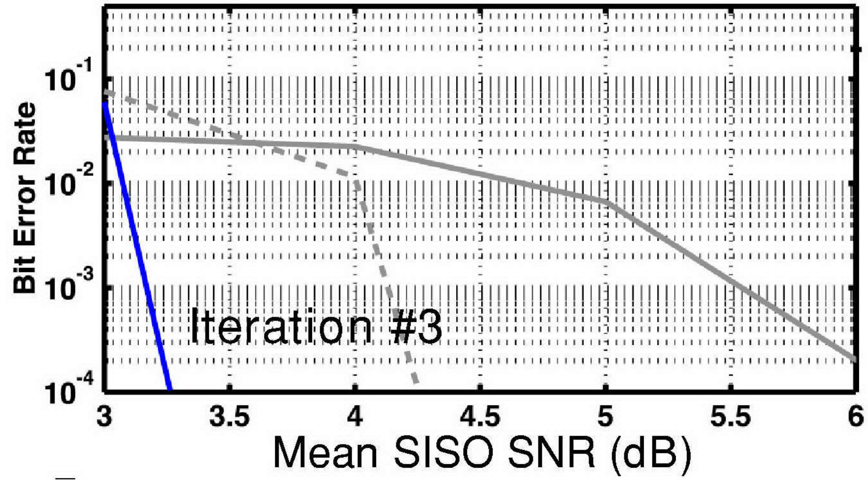
Traning-based
Space-Frequency Filter



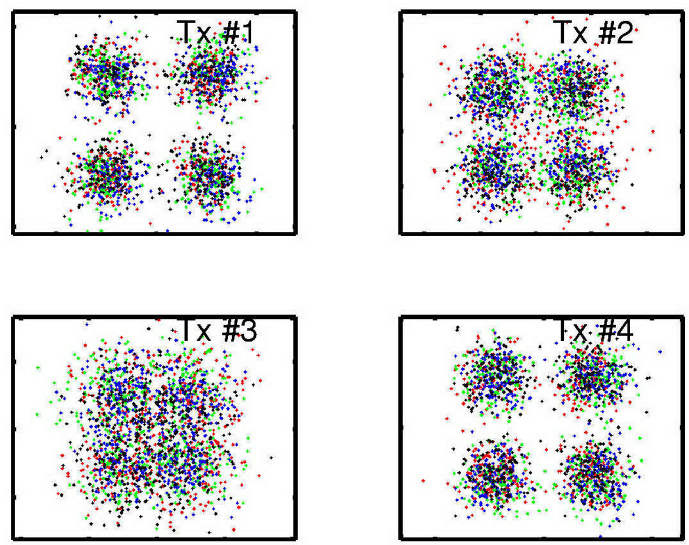
Data-Directed
Space-Time-Frequency Filter



Receiver Bit Error Rate

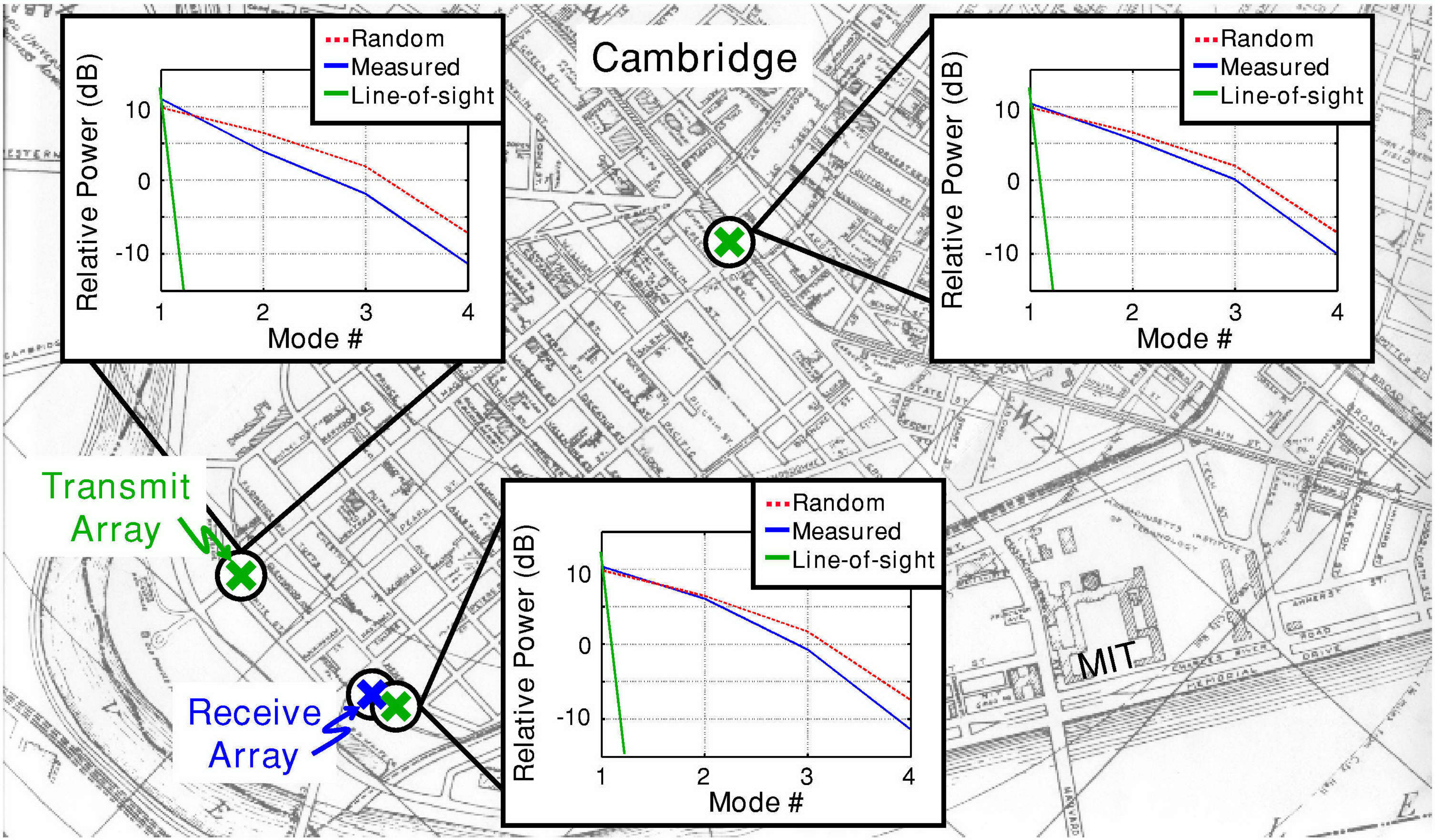


Space-Time-Frequency Filter
With Multiuser Detection

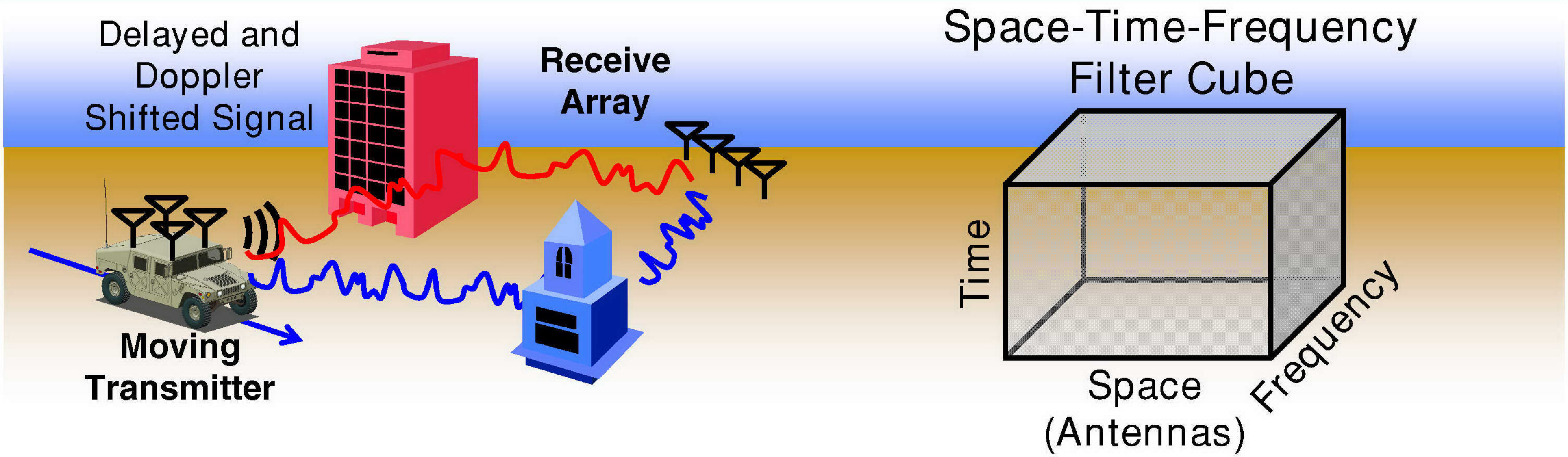


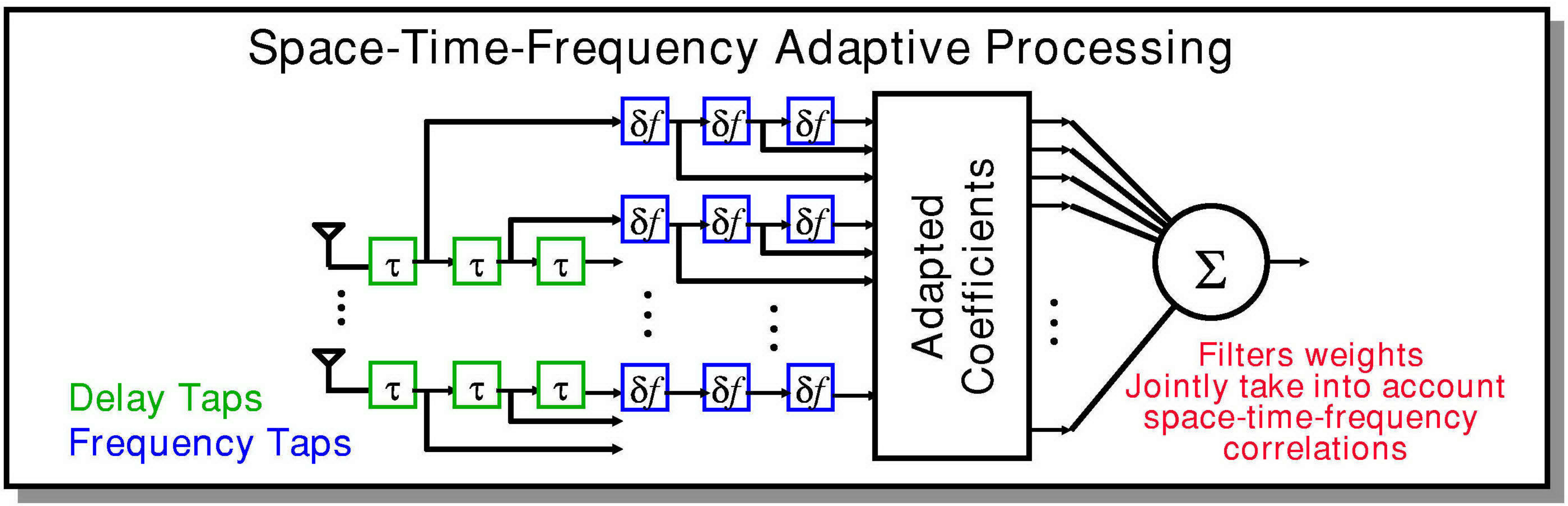
Channel Modes

Experimental Results



Adaptive Beamforming in Multipath





Notional Multiuser Detection